Internal Solitons in the Northeastern South China Sea Part I: Sources and Deep Water Propagation

Steven R. Ramp, Tswen Yung Tang, Timothy F. Duda, James F. Lynch, *Senior Member, IEEE*, Antony K. Liu, Ching-Sang Chiu, Frederick L. Bahr, Hyoung-Rok Kim, and Ying-Jang Yang

***Abstract*—A moored array of current, temperature, conductivity, and pressure sensors was deployed across the Chinese continental shelf and slope in support of the Asian Seas International Acoustics Experiment. The goal of the observations was to quantify the water column variability in order to understand the along- and across-shore low-frequency acoustic propagation in shallow water. The moorings were deployed from April 21–May 19, 2001 and sampled at 1–5 min intervals to capture the full range of temporal variability without aliasing the internal wave field. The dominant oceanographic signal by far was in fact the highly nonlinear internal waves (or solitons) which were generated near the Batan Islands in the Luzon Strait and propagated 485 km across deep water to the observation region. Dubbed trans-basin waves, to distinguish them from other, smaller nonlinear waves generated locally near the shelf break, these waves had amplitudes ranging from 29 to greater than 140 m and were among the largest such waves ever observed in the world's oceans. The waves arrived at the most offshore mooring in two clusters lasting 7–8 days each separated by five days when no waves were observed. Within each cluster, two types of waves arrived which have been named type-a and type-b. The type-a waves had greater amplitude than the type-b waves and arrived with remarkable regularity at the same time each day, 24 h apart. The type-b waves were weaker than the type-a waves, arrived an hour later each day, and generally consisted of a single soliton growing out of the center of the wave packet. Comparison with modeled barotropic tides from the generation region revealed that: 1) The two clusters were generated around the time of the spring tides in the Luzon strait; and 2) The type-a waves were generated on the strong side of the diurnal inequality while the type-b waves were generated on the weaker beat. The position of the Kuroshio intrusion into the Luzon Strait may modulate the strength of the waves being produced. As the waves shoaled, the huge lead solitons first split into two solitons then merged together into a broad region of thermocline depression at depths less than 120 m. Elevation waves sprang up behind them as they continued to propagate onshore. The elevation waves also grew out of regions where the locally-generated internal tide forced the main thermocline down near the bottom. The "critical point" α where the upper and lower layers were equal was a good indicator of when the depression or elevation waves would form, however this was not a static point, but rather varied in both space and time according to the presence or absence of the internal tides and the incoming trans-basin waves themselves.**

***Index Terms*—Baroclinic tides, nonlinear internal waves, ocean currents.**

I. Introduction

A. The ASIAEX Program

THE Asian Seas International Acoustics Experiment (ASIAEX) was a major field effort in coupled physical oceanography, geophysics, and environmental acoustics which took place during the consecutive springs of 2000 and 2001 in the South and East China Seas. The program was divided into two major components, a volume interaction experiment in the South China Sea (SCS), with Taiwan and Singapore as the primary collaborators, and a boundary interaction experiment in the East China Sea (ECS), with the People's Republic of China (PRC) and Korea as the primary international partners. The overarching goal of the SCS volume interaction experiment was *to understand acoustic propagation through shallow water when strong oceanic variability in the form of fronts, eddies, boundary layers, and internal waves, is present*. The goal of the boundary interaction experiment was to *develop models that can predict the mean reverberation level and fluctuations using measured environmental parameters*. Both experiments were multiship operations and required close cooperation between acousticians, physical oceanographers, and geophysicists. All the partnering nations contributed human and financial resources to the program, which allowed a larger and more comprehensive experiment than would otherwise have been possible. This paper presents results from the SCS volume interaction experiment. Results from the ECS program are presented elsewhere in this special issue.

The science plan for the 2001 SCS experiment called for simultaneous observations of the water column properties (temperature, salinity, and velocity) and acoustic propagation characteristics at very high resolution in space and time. This was accomplished by a combination of moored and shipboard observations near the continental shelf break between the southern tip of Taiwan and Dongsha Island (also called Pratis Reef) bounded by 21 to 22.5°N, 117 to 119°E (Fig. 1). The moored array consisted of seven densely instrumented oceanographic moorings (S8–S2) deployed in an across-shelf line spanning 800 to 72 m

Manuscript received June 6, 2003; revised April 2, 2004. The planning, execution, and analysis of this work was supported by the U.S. Office of Naval Research Ocean Acoustics and Physical Oceanography Programs. Significant funding contributions were also made by the National Science Council of Taiwan.

S. R. Ramp, C.-S. Chiu, and F. L. Bahr are with the Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943 USA.

T. Y. Tang is with the Institute of Oceanography, National Taiwan University, Taipei, ROC.

H.-R. Kim was with the Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943 USA. He is now at Seoul National University, Seoul, South Korea.

T. F. Duda and J. F. Lynch are with the Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA.

A. K. Liu is with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

Y.-J. Yang is with the Chinese Naval Academy, Kaohsiung, Taiwan, ROC.

Digital Object Identifier 10.1109/JOE.2004.840839

(Fig. 1). These moorings were designed to be along the primary acoustic transmission paths. Two sound sources operating at 224 and 400 Hz were deployed on the 350 m isobath and sources operating at 300, 400, and 500 Hz were deployed on the 120 m isobath (Fig. 1). The acoustic signals were all received at an L-shaped hydrophone array with both horizontal and vertical apertures, also moored on the 120 m isobath. While the acoustics results are not explicitly discussed in this paper, the mooring locations are included to foster comparisons presented elsewhere [1], [2].

While the moorings were in the water, shipboard surveys continuously mapped the area to ascertain the three-dimensional spatial scales and representativeness of the moorings. On the OCEAN RESEARCHER 1 (OR1), two surveys were conducted using the SeaSoar towed undulating vehicle: The small-scale SeaSoar survey mapped the three-dimensional water mass properties in the insonified region and a larger-scale survey described the surrounding mesoscale variability [3]. A second vessel, the OCEAN RESEARCHER 3 (OR3) steamed dedicated cruise tracks in the vicinity of the acoustic transmission paths [4]. Both vessels collected temperature, conductivity, and hull-mounted ADCP velocity data as a function of pressure (depth). The SeaSoar aboard OR1 additionally sampled fluorescence, bioluminescence, and light transmission while the OR3 sampled high frequency acoustic backscatter at 200 and 350 kHz for flow visualization of internal waves and evaluation of turbulence.

V. Summary and Conclusion

A combination of moored and shipboard observations were made near the continental shelf break in the South China Sea between the southern tip of Taiwan and Dongsha Island as part of the Asian Seas International Acoustics Experiment (ASIAEX). The moored array, which is the focus of this paper, consisted of eight densely-instrumented oceanographic moorings with seven deployed in an across-shelf line spanning 800 to 72 m depth and the eighth moored alongshore on the 80 m isobath. The moorings sampled velocity, temperature and conductivity at intervals sufficient to resolve the high frequency internal wave field as well as the tidal and mesoscale motions. The moorings were in the water for 28 days during 21 April–19 May 2001.

The most energetic motions by far turned out to be the highly nonlinear internal soliton packets propagating through the array. The largest waves can be clearly identified as trans-basin waves which were generated in the Luzon Strait and propagated about 485 km toward the WNW before encountering the most offshore mooring. Inverse ray tracing identified the most likely sources as over the Luzon Ridge near the Batan Islands, in agreement with earlier work. Unfortunately no in-situ observations were made near the islands, but comparison with two independent global tidal models indicates that the waves were generated around the time of the spring tide in the straits, in agreement with other sites around the world.

The trans-basin depression waves arrived at the offshore mooring in two clusters lasting 7–8 days each separated by five days when no waves were observed. The waves in the later cluster had much greater amplitude than the waves in the earlier cluster. Within each cluster, two types of waves arrived which have been named type-a and type-b. The type-a waves had greater amplitude than the type-b waves and arrived with remarkable regularity at the same time each day, 24 h apart. These waves resembled other soliton packets reported in the literature, with the largest soliton leading and an approximately rank-ordered structure behind. The type-b waves were weaker than the type-a waves, arrived an hour later each day, and generally consisted of a single soliton growing out of the center of the wave packet. The type-b waves do not resemble waves observed at other sites and represent some new generation and propagation process. Both types of wave arrivals were associated with a tidal bore. The initial tidal bore associated with the a-waves was larger than the one associated with the b-waves. The amount of energy in the tidal bore/internal waves decreased/increased each day as the solitons strengthened from May 6–9. Given the strong diurnal inequality evident in the modeled barotropic tides for the generation region, the type-a waves were apparently generated on the strong side of the diurnal inequality while the type-b waves were generated on the weaker beat. The timing of the wave arrivals is consistent with the type-a waves being generated primarily by the non-progressing K1 tide while the type-b waves were generated by the M2 tidal constituent.

As the waves traveled up the continental slope from 350 to 200 m depth, the huge lead solitons began feeling the bottom. These waves were forced up and out by the bottom, creating reduced amplitude and greater half-amplitude width. Some the largest solitons split into two lead solitons. Starting around May 10, the local spring tide, a second tidal bore appeared which was diurnal, out of phase with the offshore bore, and presumed to be locally generated. The new bore interacted with the incoming solitons, smearing them out during the May 10–13 time frame. All the solitons remained depression waves at the 200 m isobath.

The wave field was radically transformed by the time it reached the 120 m isobath. What had initially been the large-amplitude lead soliton (or solitons) now formed a broad region of thermocline depression, and elevation waves sprang up behind it. The local tidal bore also depressed the thermocline all the way to the bottom for twelve hours at a time, and elevation waves grew out of this region also. Some depression waves still existed during the other phase of the internal tide when the thermocline was high. The relatively simple idea of a critical point (upper and lower layer depths equal) at some isobath as the bottom shoals under a relatively constant-depth thermocline was inadequate to describe the wave field. The critical point was a dynamic, rather than a static location, and changed its position often in response to the passage of the tidal bore and even the internal waves themselves.

The modal structure of the waves, both depression waves and elevation waves, showed remarkable agreement with the theory. Offshore, the depression waves were almost all mode-1 waves, with strong orbital velocities in the direction of wave propagation in the upper layer and toward the opposite direction in the lower layer. The nodal point statistically occurred around 140 m but was not well resolved by the spacing of the deeper current meters. The ADCP observed vertical velocities (w) as large at 60 cm s^{-1} in the largest soliton. Large downward vertical velocity preceded the arrival of each thermocline depression, and large upward w followed along behind. The wave polarity reversed in the elevation waves with a nodal point near 66 m over the 120 m isobath. There was upward flow ahead of the wave, onshore (upslope) flow along the bottom, and downward vertical velocity behind the wave. The elevation waves were less dispersed than the trans-basin waves, due to their local generation.